N73-18724

NGL-05-007-190

PLASMA PHYSICS GROUP

The Formation of Ion Acoustic Shocks

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PPG-142

January 1973

UNIVERSITY OF CALIFORNIA
LOS ANGELES

ENGINEERING

PHYSICS

METEOROLOGY

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1.0 Introduction

Recent experiments performed in the UCLA double plasma (DP) device[1] have verified the existence of electrostatic ion acoustic laminar shocks. These shocks were first predicted theoretically by Moiseev and Sagdeev[2] from the cold ion-Boltzmann electron steady state fluid equations. In order to obtain a shock-like transition rather than solitons, Moiseev and Sagdeev[2] argued that a small number of reflected ions was required. Montgomery and Joyce[3] later showed that shock-like transitions were also possible if a distribution of electrons trapped in the shock potential was assumed. However, in the DP experiments there exists a third possibility for explaining the formation of laminar shocks, i.e., that the method of shock excitation, the piston, determines the resultant shock structure. In this paper we investigate the influence of the piston on the shock structure by modeling the DP device and by numerically solving the temporal and spatial evolution of the shock. In order to isolate piston effects, as opposed to kinetic theory effects such as reflected ions and trapped electrons, we model the DP plasma as a cold ion fluid with isothermal Boltzmann electrons. We show that on the time scale of the experiments laminar shock transitions with structure agreeing with DP shock experiments can be excited.

2.0 Model of DP Device

The DP device consists of two plasmas separated by a negatively biased grid whose potential greatly exceeds the electron thermal potential T_e/e; T_e is the electron temperature in energy units and e is the electronic charge. Since the electron distribution functions are essentially Maxwellian, the grid serves to electrically isolate the two plasmas so that the potential of each plasma can be varied independently. Shock excitation consists of raising the potential in one plasma (driving chamber) as a linear (ramp) function of time until a fixed potential height is achieved; after this time the potential is held constant. Ions flow into the second (target) plasma, and the resulting charge neutralization by electrons excites a large amplitude ion acoustic wave which propagates into the target plasma and steepens into a shock.

Since the physics of the sheath around the separation grid involves kinetic theory effects which we wish to avoid, we model the DP plasma using a modified Boltzmann electron equation of state

$$n_e = n_o \exp\left[e\left(\frac{\varphi(x,t) - \varphi_1(x,t)}{T_e}\right)\right] \tag{1}$$

where $\varphi(x,t)$ is the potential. $\varphi_1(x,t)$ simulates the DP grid by having different values in the two halves of the machine. For the purpose of numerical stability, the discontinuity in φ from its value, p(t) at the wall of the driving chamber $(x/z << -1)$

to the value $\varphi = 0$ at the target chamber wall ($x/z \gg 1$) was spread out over several Debye scale lengths, $k_D^{-1} = \left[T_e/4\pi\, n_o e^2\right]^{-\frac{1}{2}}$, giving a φ_1 which is continuous and has continuous derivatives

$$\varphi_1(x,t) = \frac{p(t)}{2}[1 - \tanh(x/z)]. \tag{2}$$

Here $p(t)$ has the temporal form of a truncated ramp (cf. Figure 1a) and z is the effective width of the sheath, chosen to be several k_D^{-1}. In the target chamber and outside the sheath ($x/z \gg 1$), $\varphi_1 \to 0$ so that in the region of shock propagation a Boltzmann ansatz, $n_e \propto \exp\left(e\varphi/T_e\right)$ for the electrons is appropriate. Computations run with different sheath sizes (z) were not appreciably different, so our neglect of the exact sheath dynamics probably does not seriously affect the shock structure.

The ion equations of motion are

$$\frac{\partial n}{\partial t} + \frac{\partial}{\partial x}\left(n\ v_i\right) = 0$$

$$\frac{\partial v_i}{\partial t} + v_i \frac{\partial v_i}{\partial x} = -\frac{\partial \psi}{\partial x} \tag{3}$$

where spatial distance x is measured in units of k_D^{-1} and time is in units of the ion plasma frequency $\omega_{p_i} = \left[\frac{4\pi\ n_o\ e^2}{m_i}\right]^{\frac{1}{2}}$;

$\psi = \frac{e\varphi(x,t)}{T_e}$; and n is the ion density normalized to n_o. The electrons, ions, and the potential are coupled through the Poisson equation

$$\frac{d^2\psi}{dx^2} = e^{\psi - \psi_1} - n \tag{4}$$

All plasma motions are confined to the x-direction, and the plasma is assumed uniform in transverse directions.

In the numerical analysis, the Poisson equation was solved by iterated Fourier transforms. In order to avoid difficulties associated with the Gibbs phenomenon, we introduce the function

$$A(x,t) = \psi(x,t) - \psi_1(x,t) \tag{5}$$

so that $A(a,t) = A(b,t) = 0$ where $x = a(x = b)$ is the wall of the driving (target) chamber. $A(x,t)$ then satisfies the differential equation

$$\frac{d^2A}{dx^2} - A = U(A)$$

$$U(A) = e^A - A - n - \frac{d^2\psi_1}{dx^2} \tag{6}$$

where $U(a) = U(b) = 0$. After obtaining the solution to the Poisson equation, the electric field $E(x,t)$ is calculated, and is used to step the position, velocity and density ahead in time along the Newtonian characteristics of the differential equation

$$x = x' + \left[\frac{v(x',t) + v(x,t+\Delta)}{2}\right]\Delta + E(x',t)\frac{\Delta^2}{2}$$

$$v(x,t+\Delta) = v(x',t) + E(x',t)\Delta$$

$$n(x) = n(x')\frac{dx'}{dx} \tag{7}$$

where Δ is the time step. The procedure is then iterated. To avoid numerical instabilities, the spatial grid size is chosen to be compatible with Δ. Numerical diffusion speeds can be shown to be negligible compared with wave propagation speeds.

3.0 Simulation of DP Shocks

To excite large amplitude ion waves in the target chamber, the potential p(t) on the driving chamber's wall is raised to various levels as a linear ramp in a time comparable to $\omega_{p_i}^{-1}$. A compressional ion acoustic wave propagates into the target chamber and steepens into a laminar shock; a rarefaction ion acoustic wave propagates into the driving chamber. Figure 1b shows the spatial profile of the potential for the steepening ion wave at various times after the start of excitation. By time 459 $\omega_{p_i}^{-1}$, the wave front has propagated a distance of 567 k_D^{-1} into the target chamber and has reached a quasi-steady spatial structure with a sharp leading edge of the order of 10 k_D^{-1} thick and a trailing wave train of slightly longer oscillation length.

The shock structure remained essentially unchanged for the rest of the run. The final Mach number (M) of the shock was M = 1.25 and the potential jump $\Delta\psi$ to the first maximum was $\Delta\psi = 0.46$. Included in Figure 1 is an experimental DP shock from Taylor et al.[1] with a Mach number M = 1.15 and an electron-to-ion temperature ratio of 30, chosen so as to minimize the number of reflected ions. The computed shock reproduces the essential features of the spatial structure of the experimental shocks.

By varying the height of the driving chamber potential p(t), shocks with different Mach numbers and potential jumps can be launched. Figure 2 shows $\Delta\psi$ vs. ramp height ep/T_e for Mach numbers 1.06 - 1.4. In Figure 3 the Mach number is plotted against $\Delta\psi$. The solid points are from the computations; the lower solid curve is the theoretical M vs. $\Delta\psi$ relation calculated by Moiseev and Sagdeev[2] for a steady state shock

$$M^2 = \frac{1}{2}\frac{\left[e^{\Delta\psi} - 1\right]^2}{e^{\Delta\psi} - 1 - \Delta\psi} \tag{8}$$

The good agreement seen in Figure 3 indicates that the computed shocks did achieve a quasi-steady state shock flow. They are, of course, not completely steady, owing to propagation of the rarefaction wave into the driving chamber. Furthermore, this agreement indicates that our modified Boltzmann electron equation of state used to model the DP grid does not significantly affect the quasi-steady shock structure. Also shown in Figure 3 are two points (open circles) which were calculated using, instead of the Boltzmann ansatz for electrons, the trapped electron equation of state discussed by Forslund and Shonk[4] and Forslund and Freiberg[5]. (The two differ only for electrons with kinetic energy $mv^2/2 < mv_0^2/2 \equiv e\varphi(x)$. The Boltzmann ansatz assumes a distribution function $f(x,v) = f(x,v_0)\exp\left[m\left(v_0^2-v^2\right)/2T_e\right]$ whereas Forslund and Freiberg[5] assume $f(x,v) = f(x,v_0)$.) Their M vs. $\Delta\psi$ relationship is

$$M^2 = \frac{1}{2}\frac{[F-1]^2}{F-1-\Delta\psi}$$

$$F = \frac{2}{\sqrt{\pi}}\sqrt{\Delta\psi} + e^{\Delta\psi}\,\mathrm{erfc}\left(\sqrt{\Delta\psi}\right) + \frac{4}{3\sqrt{\pi}}(\Delta\psi)^{3/2} \tag{9}$$

and the computed shocks again agree with theoretical predictions. Finally, the dashed curve in Figure 3 is the experimental M vs. $\Delta\psi$ relation, $M = 1.0 + 0.6\Delta\psi$, obtained by Means <u>et al.</u>[6] in the DP device. Means <u>et al.</u>[6] have shown that the experimental M vs. $\Delta\psi$ relation can be explained by a combination of trapped electrons and a reflected ion distribution function which has been flattened because of unstable ion acoustic turbulence driven by the reflected ions. Since in our computations the ions were assumed cold, we do not expect to reproduce this experimental M vs. $\Delta\psi$ relation.

In conclusion, we have shown that the spatial profile of the shock structure observed in experiments is probably a consequence of the DP ramp method of shock excitation, since quasi-steady laminar shock transitions can be formed even in the absence of reflected ions or trapped electrons. The importance of considering the piston's influence on shock structure is further emphasized by recalling that the steady state fluid theory of Moiseev and Sagdeev[2] predicted only solitons, and not shock transitions. Finally, the agreement between piston-excited and steady state theoretical M vs. $\Delta\psi$ relations indicates that both Mach number and shock potential jump are relatively insensitive to the method of shock excitation.

ACKNOWLEDGEMENTS

It is a pleasure to acknowledge beneficial discussions with Professors C.F. Kennel and A.Y. Wong. The computations were performed at the UCLA On Line computer facility.

This was partially supported by the Office of Naval Research, Grant #N00014-69-A-0200-4023 and the National Aeronautics and Space Administration, Contract NGL 05-007-190.

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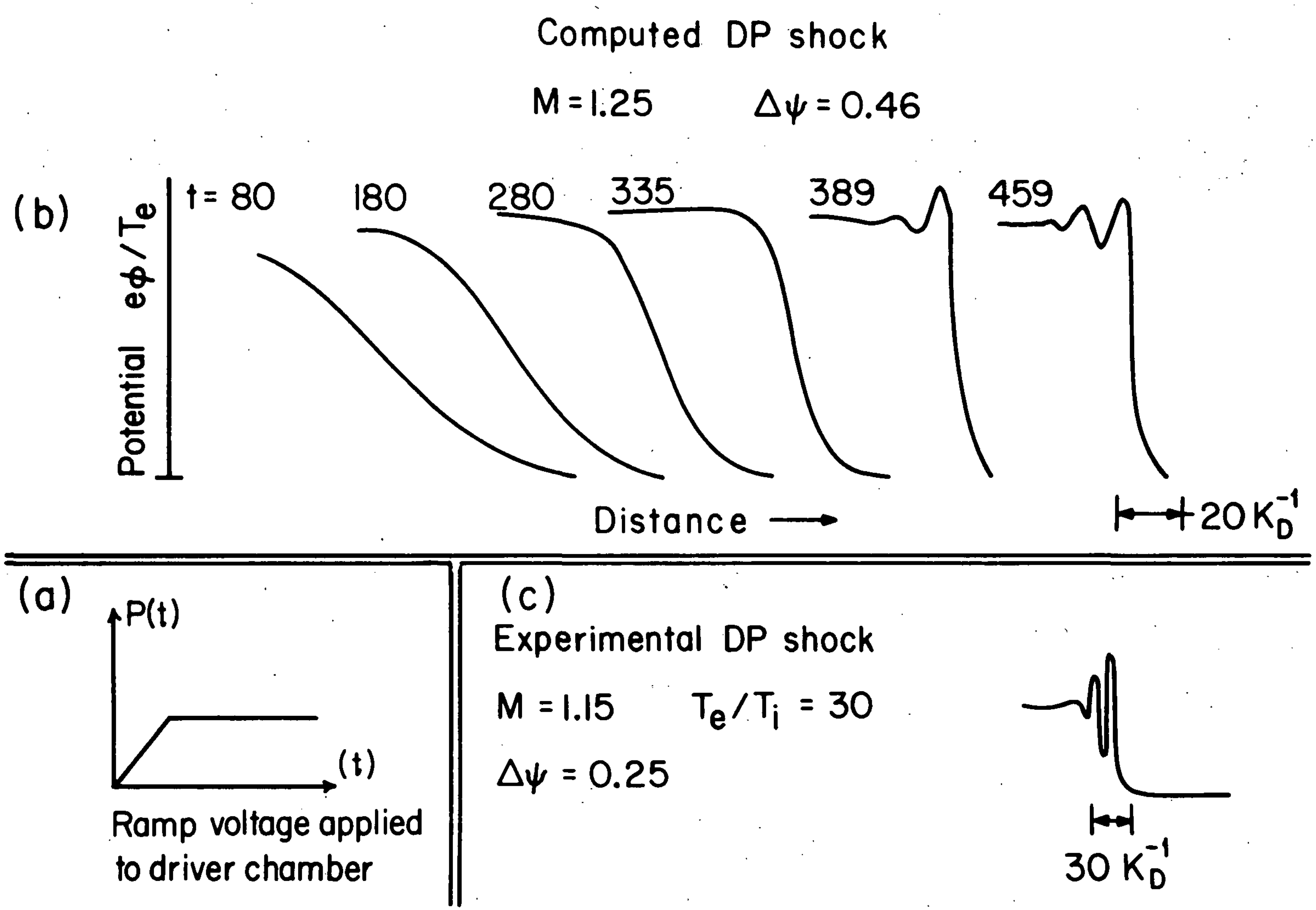
FIGURE CAPTIONS

Figure 1. a) Ramp voltage signal p(t) applied to the wall of the driving chamber; b) The propagation and steepening of an ion acoustic pulse and the formation of an ion acoustic shock; c) Experimental DP shock electron density profile from Taylor *et al.*[1].

Figure 2. The final, quasi-steady shock potential jump $\Delta\psi$ as a function of the maximum ramp driving potental ep/T_e.

Figure 3. The final, quasi-steady shock Mach number M vs. the shock potential jump $\Delta\psi$. The points are from the numerical computations (solid circles for Boltzmann equation of state, open circles for trapped electron equation of state). The solid curves are the theoretical relations for the Boltzmann and trapped electron


Computed DP shock
M = 1.25 Δψ = 0.46
(b)
Potential eφ/Te
t = 80
180
280
335
389
459
Distance →
20 K_D^-1
(a)
P(t)
(t)
Ramp voltage applied to driver chamber
(c)
Experimental DP shock
M = 1.15 Te/Ti = 30
Δψ = 0.25
30 K_D^-1

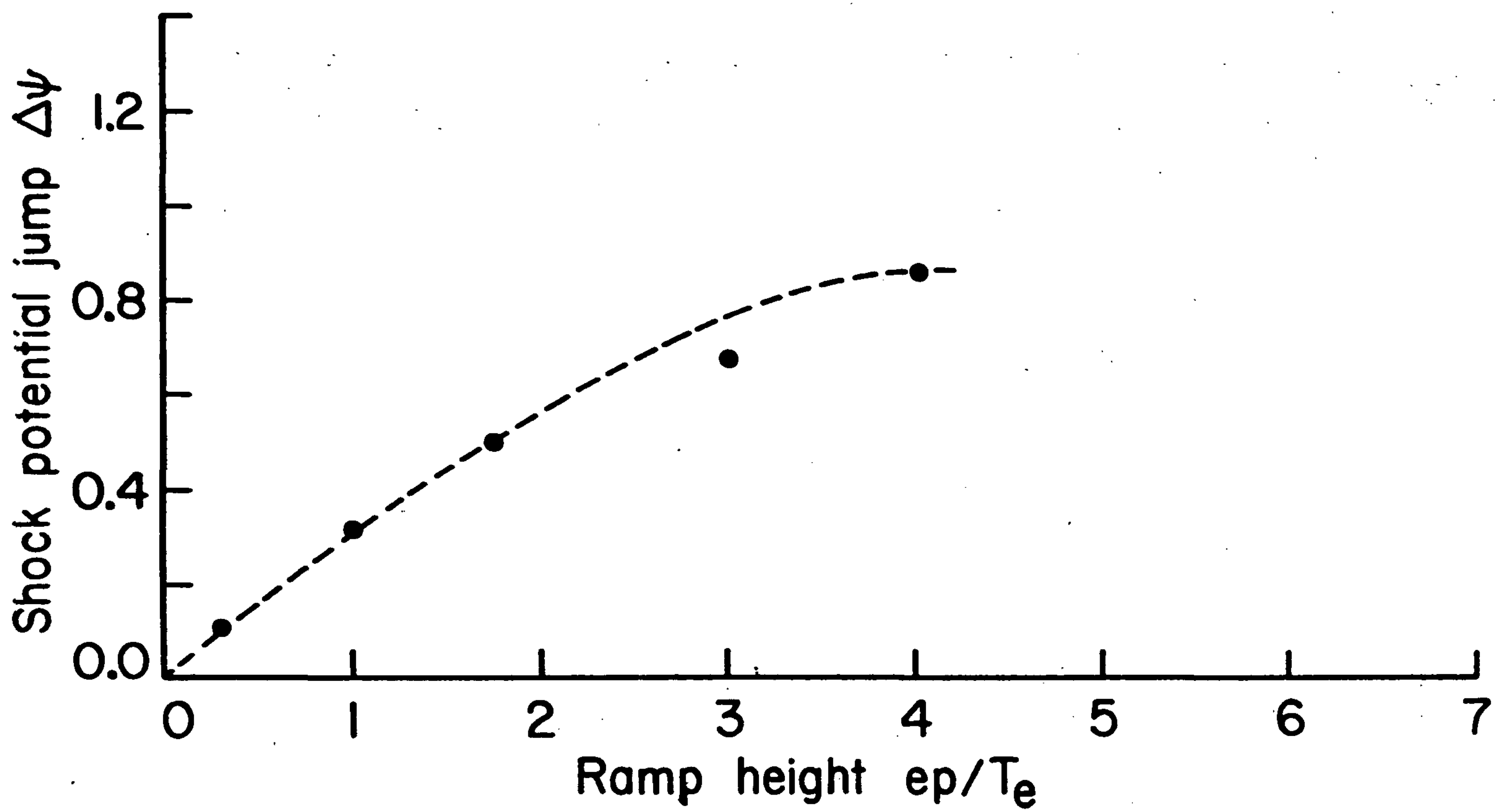
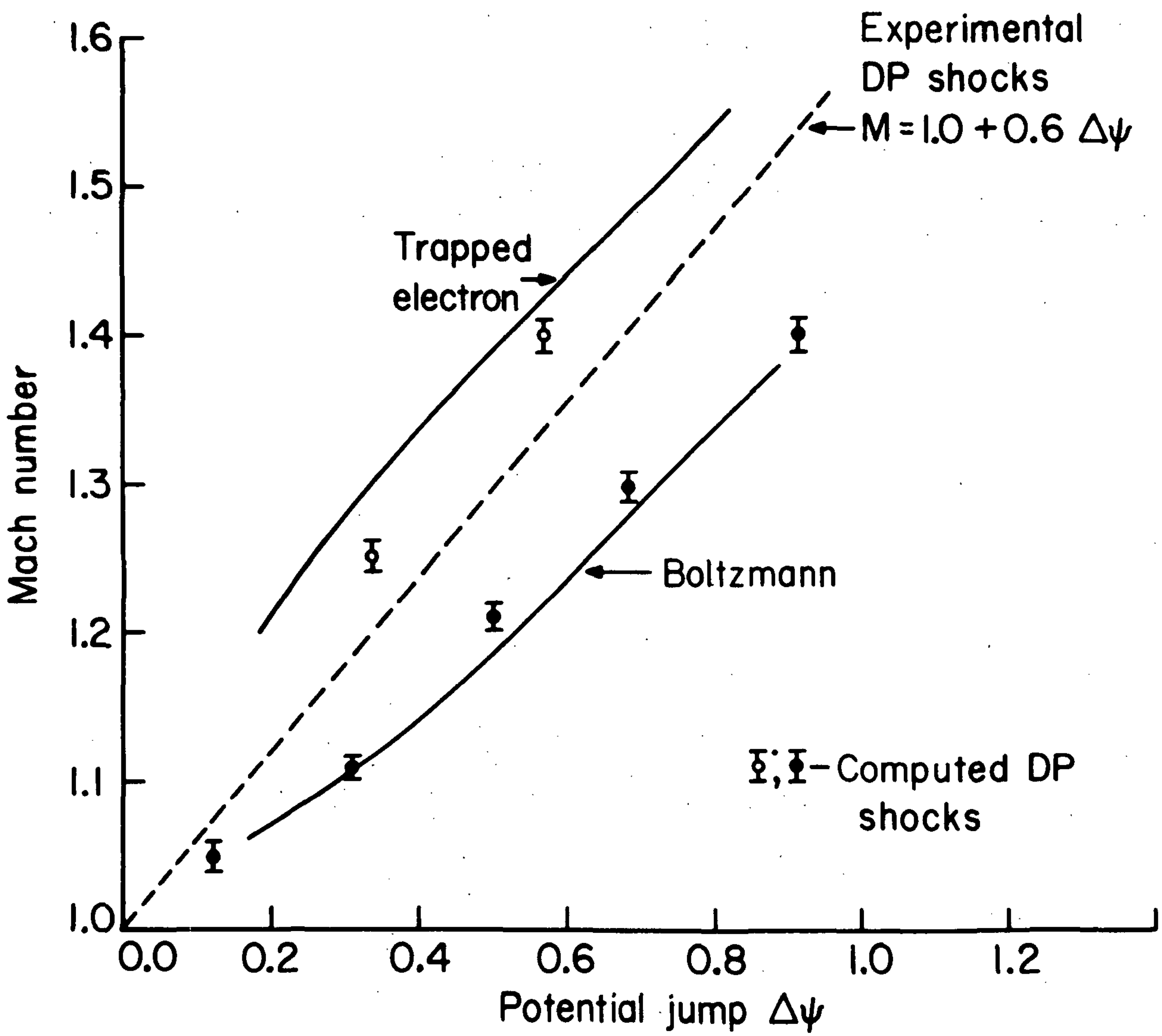

Shock potential jump Δψ
1.2
0.8
0.4
0.0
0
1
2
3
4
5
6
7
Ramp height ep/Te

Figure 2



Experimental
DP shocks
M = 1.0 + 0.6 Δψ
Trapped
electron
Boltzmann
Computed DP
shocks
Mach number
Potential jump Δψ
1.0
1.1
1.2
1.3
1.4
1.5
1.6
0.0
0.2
0.4
0.6
0.8
1.0
1.2

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